ISSN 0021-3640, JETP Letters, 2024, Vol. 120, No. 6, pp. 381–387. © The Author(s), 2024. This article is an open access publication.
Russian Text © The Author(s), 2024, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2024, Vol. 120, No. 6, pp. 393–399.

FIELDS, PARTICLES, AND NUCLEI

Observation of the Polarization of Λ Hyperons Produced in the Interaction of K^- Mesons with Nuclei

V. V. Abramov[a], V. V. Moiseev[a], I. G. Alekseev[b], N. A. Bazhanov[c], N. S. Borisov[c], A. N. Vasiliev[a,d], Yu. M. Goncharenko[a], I. S. Gorodnov[c], A. B. Gridnev[e], N. K. Kalugin[a], N. G. Kozlenko[e], Yu. M. Melnik[a], A. P. Meshchanin[a], N. G. Minaev[a], D. A. Morozov[a], V. V. Mochalov[a,d,*], A. B. Neganov[c], V. M. Nesterov[b], K. D. Novikov[a], D. V. Novinskii[e], L. V. Nogach[a], M. B. Nurusheva[d], A. F. Prudkoglyad[a], S. V. Ryzhikov[a], V. L. Rykov[d], V. V. Ryltsov[b], A. V. Ryazantsev[a], E. I. Samigullin[b], D. N. Svirida[a], P. A. Semenov[a,d], A. V. Uzunyan[a], Yu. A. Usov[c], and A. E. Yakutin[a]

[a] *Logunov Institute for High Energy Physics, National Research Center Kurchatov Institute, Protvino, Moscow region, 142281 Russia*
[b] *National Research Center Kurchatov Institute, Moscow, 123182 Russia*
[c] *Joint Institute for Nuclear Research, Dubna, Moscow region, 141980 Russia*
[d] *National Research Nuclear University MEPHI (Moscow Engineering Physics Institute), Moscow, 115409 Russia*
[e] *Konstantinov Petersburg Nuclear Physics Institute, National Research Center Kurchatov Institute, Gatchina, 188300 Russia*
**e-mail: mochalov@ihep.ru*

Received July 30, 2024; revised August 13, 2024; accepted August 13, 2024

First results on the polarization of Λ hyperons inclusively produced on 26.5-GeV/c K^- and π^- beams are presented. The measurements were carried out using the SPASCHARM setup at the U-70 accelerator facility (Protvino, Russia) on nuclear targets in 2021 and 2022. The polarization of an Λ hyperon on the π^- beam does not exceed several percent in most of the studied kinematic region. The data obtained on the K^--meson beam exhibit a significant positive polarization at large values of the Feynman variable x_F and transverse momentum p_T measured for the first time on nuclei.

DOI: 10.1134/S0021364024602811

1. INTRODUCTION

The polarization of Λ hyperons in the exclusive $K^-p \to \Lambda\pi^0$ reaction reaches its maximum possible value $P_N = 0.98 \pm 0.15$ at low (about 3 GeV) energy [1]. It is therefore of interest to measure the polarization of Λ hyperons in an inclusive reaction at a higher energy, especially in scattering on nuclei, which has not yet been done.

The transverse polarization in the inclusive production of Λ hyperons was discovered in 1976 in the interaction of unpolarized 300-GeV protons with a stationary beryllium target [2]. Contrary to expectations, the polarization turned out to be significant, whereas it was assumed that a large number of various final states containing a Λ hyperon would suppress all polarization effects, yielding the total polarization close to zero. It turned out that, on the contrary, significant spin effects persist even at high energies. In subsequent experiments, the polarization of Λ hyperons was studied in various hadron–proton, hadron–nucleus, and nucleus–nucleus interactions in a wide energy range (see, for example, review [3]).

A number of theoretical, primarily phenomenological, models have been developed that explain individual features of data [4–9].

The observed spin effects may be of a non-perturbative nature associated with the spontaneous breaking of the chiral symmetry in QCD and the appearance of an additional mass of about 300 MeV and a large negative anomalous chromomagnetic moment in the constituent quarks [9, 10]. The inhomogeneous chromomagnetic field that arises during interaction of hadrons, which leads to the effect of quark polarization, similar to the polarization of atoms in the famous Stern–Gerlach experiment [11] can play an important role in the emergence of hyperon polarization. The precession of the quark spin in a strong chromomagnetic field manifests itself as polarization oscillations depending on x_F. This approach makes it possible to explain the phenomenology of polarization phenomena within a single mechanism and make a number of predictions that are critical for existing models [10].

The main goal of the SPASCHARM (SPin ASymmetries in CHARM production) [12] experiment conducted at the U-70 accelerator complex is a systematic study of spin effects in the inclusive production of various particles and resonances in the interaction of hadrons at energies of several tens of GeV. The experiment was carried out at moderate transverse momenta of the produced particles, which correspond to the region of nonperturbative quantum chromodynamics, where perturbation theory is inapplicable. Such data are essential for the development of a theoretical apparatus for this complex kinematic region. Measuring the polarization of hyperons in reactions with meson beams is of interest because the incident hadron contains simultaneously quarks and antiquarks, including strange ones.

2. EXPERIMENT

The transverse polarization of hyperons is possible due to a weak decay occurring with spatial parity violation. In the decay of the Λ hyperon with transverse polarization P into a π meson and a proton, the probability of proton emission at the angle θ_p to the hyperon polarization vector $\mathbf{P}$ has the form

$$\frac{dN}{d\Omega} = \frac{1 + \mathbf{P}\mathbf{e}_p}{4\pi} = \frac{1 + \alpha_\Lambda P \cos\theta_p}{4\pi}, \qquad (1)$$

where $\mathbf{e}_p$ is the unit vector in the proton motion direction in the hyperon rest frame and $\alpha_\Lambda = 0.732 \pm 0.014$ (it is assumed that $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$ [13]). Due to the conservation of parity in strong interactions, the vector $\mathbf{P}$ is directed along the normal $\mathbf{n}$ to the plane of scattering set by the momenta of the incident hadron $\mathbf{p}_a$ and the produced hyperon $\mathbf{p}_c$: $\mathbf{n} = (\mathbf{p}_a \times \mathbf{p}_c)/|\mathbf{p}_a \times \mathbf{p}_c|$.

The measurements were carried out at the Logunov Institute for High Energy Physics, National Research Center Kurchatov Institute on the beamline 14 at the U-70 accelerator facility. The SPASCHARM setup is described in detail in [14]. Negatively charged particles π^- (~98%), K^- (~1.5%), and $\bar{p}$ (~0.3%) with a momentum of 26.5 GeV/c were extracted to the setup target. The beam particles are selected by a telescope consisting of three scintillation counters. A counter with a diameter of 14 mm, which is located at the input of the target zone, limits the size of the beam used.

Beam particles were identified by three threshold Cherenkov counters. Two counters detected π^- mesons and lighter particles, while the third also recorded K^- mesons. The coordinates and angles of the beam particles were measured by beam hodoscopes, including a high-precision fiber hodoscope [15].

A set of seven different nuclear targets from carbon to lead and an "empty" target were used in the measurements. The thickness of the targets was 5–10% of the interaction length.

In 2021, an interaction trigger was used, while in 2022, the presence of a K^- meson in the beam was additionally required, which made it possible to increase the rate of K^- meson collection by a factor of 4 due to the suppression of π^- mesons. The admixture of π^- mesons in the K^- meson beam, which is determined by the inefficiency of Cherenkov counters, does not exceed 3% of their number. The interaction trigger is formed when the signals from the beam telescope coincide in the absence of a signal from the additional BK (beam killer) trigger counter, located at the very end of the setup (after the track detectors in front of the electromagnetic calorimeter). The BK counter, which has a diameter of 10 cm, records beam particles that have passed the target without interaction.

Secondary charged particles are detected by proportional chambers and drift tubes (57 layers in total). To minimize systematic errors, track detectors of the setup were optimized (by the selection of flowing speed and operating voltage) [14], which ensured the stability of all detectors of no worse than 0.3%. A wide-aperture spectrometric magnet with a field integral of about 0.7 T m is used to measure the momentum [16].

In total, 1.1×10^9 events were detected in 2021. The number of events with identified beam pions and kaons were 856×10^6 and 21.2×10^6, respectively. In 2022, the number of identified beam particles is 67.1×10^6, of which 48.5×10^6 contained K^- mesons.

3. ANALYSIS OF EXPERIMENTAL DATA

The experimental reconstruction program is based on the software package used in the PANDA experiment at the Facility for Antiproton and Ion Research (FAIR, Darmstadt, Germany) [17]. To reconstruct the tracks of charged particles, a track search method known as the Hough transform is used.

Secondary vertices corresponding to the point of decay of the Λ hyperon into a proton and a π^- meson are found for all combinations of secondary tracks of the opposite sign. Next, the primary interaction vertex, i.e., the intersection point of the Λ hyperon track and the beam track, is found.

To obtain adjustments for the detection efficiency and reconstruction of particle tracks in the SPASCHARM setup, events obtained by the Monte Carlo method are used. The events were generated using the PYTHIA 8.212 generator [18]. The simulated events were traced through the SPASCHARM setup using the GEANT 3.2111 software package [19]. Since Λ hyperons are not polarized in the simulation, these events can be used to adjust the hyperon detection efficiency in the SPASCHARM setup. We ana-

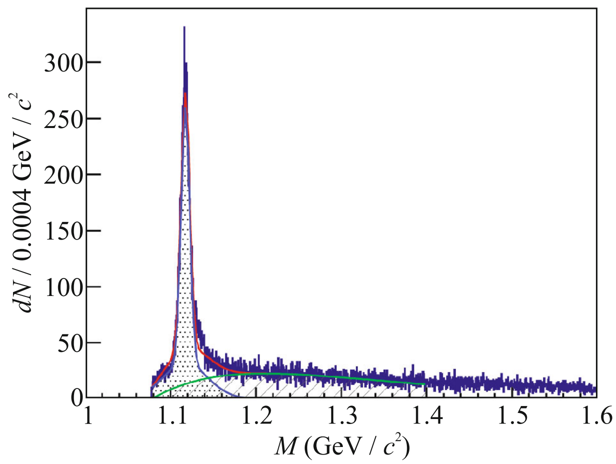

Fig. 1. (Color online) Mass distribution of $p\pi^-$ pairs in the K^- beam.

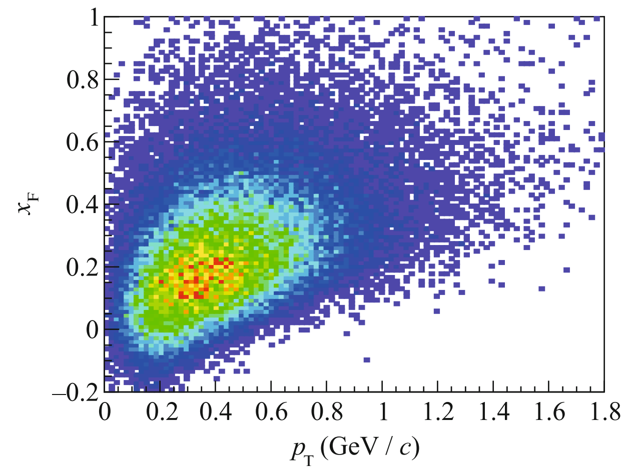

Fig. 2. (Color online) Distribution of Λ hyperons by kinematic parameters in the $\pi^- A \to \Lambda X$ reaction.

lyzed 2×10^8 Monte Carlo events. The number of Λ hyperons reconstructed in Monte Carlo events is an order of magnitude larger than their number in the data; for this reason, their contribution to the statistical error of the measured polarization is insignificant.

The following criteria were applied to select the required statistics.

• The presence of only one identified (π^- or K^-) beam track.

• The presence of two or more reconstructed tracks of secondary particles.

• The pairs of charged particles with opposite signs were selected if they satisfied the following conditions: (i) the distance between the tracks forming the secondary vertex is less than 0.4 cm, (ii) the distance between the beam track and the track of the candidate Λ hyperon is less than 0.4 cm, (iii) the distance between the primary and secondary vertices along the Z direction is larger than 18 cm, and (iv) the primary vertex is located in the target region of the experiment.

Since secondary particles are not identified, the following selection rules were additionally applied to suppress the combinatorial background.

• To identify Λ hyperons, only pairs with $\alpha_{AP} > 0$ were selected, where α_{AP} is the decay asymmetry variable on the Armenteros–Podolyansky plot [20], i.e., the ratio of the difference-to-sum of the longitudinal momenta of positively and negatively charged particles in the laboratory coordinate system.

• The masses of the $\pi^\pm$ mesons were assigned to particles from the decay of a neutral secondary particle, while pairs with a mass in the range from 0.468 to 0.525 GeV/c^2 were excluded from the Λ hyperon candidates.

An example of the mass spectrum of the selected combinations is presented in Fig. 1. The green, blue, and red lines present the background (B), which was described by the convolution of the threshold and exponential function; the Λ hyperon signal (S), which was described by the Gaussian distribution, and the sum of the signal and the background, respectively.

The obtained width of the mass distribution is $\sigma = (5.00 \pm 0.06)$ MeV/c^2 for the π^- beam and $\sigma = (5.16 \pm 0.10)$ MeV/c^2 for the K^- beam. The integrals of the functions used in the fit allow us to determine the number of detected Λ hyperons (S) and the signal-to-background ratio (S/B): $S = 43800 \pm 242$ and $S/B = 2.90 \pm 0.03$ for the pion beam, and $S = 8318 \pm 94$ and $S/B = 13.28 \pm 0.55$ for the kaon beam. Figure 2 shows the distribution of the selected pairs by kinematic parameters for the reaction $\pi^- A \to \Lambda X$. The variables x_F and p_T range from −0.2 to 1 and from 0 to 2.5 GeV/c, respectively. Due to the limited aperture of the setup, these two variables are not absolutely independent.

4. DETERMINATION OF Λ-HYPERON POLARIZATION

The polarization of the Λ hyperon is calculated according to Eq. (1). Since spatial parity is conserved in the strong interaction, a nonzero polarization of the hyperon is possible only along the normal to the plane of scattering. In this case, the distribution is plotted as a function of the cosine of the θ_p angle between the Y axis and the proton momentum. Pairs $p\pi^-$ in the mass range of 1.105–1.125 GeV/c^2 are selected as a signal, while pairs in the mass ranges of 1.077–1.10 GeV/c^2 and 1.14–1.16 GeV/c^2 (outside the Λ-hyperon peak) are used to estimate the background. To obtain maximum statistics, all types of targets were used. The average mass number of the targets is 62.

Table 1. Polarization of Λ hyperons in $\pi^- A$ and $K^- A$ collisions for all nuclei

	Results of measurements in $\pi^- A$ interaction				Results of measurements in $K^- A$ interaction			
p_T (GeV/c), x_F	$\langle p_T \rangle$, GeV/c	$\langle x_F \rangle$	P_N,%	N_Λ	$\langle p_T \rangle$, GeV/c	$\langle x_F \rangle$	P_N,%	N_Λ
All events	0.48	0.26	4.1 ± 1.4	43800 ± 242	0.51	0.30	18.4 ± 3.0	8318 ± 94
$-0.5 < x_F < 0.14$	0.33	0.06	−6.7 ± 3.0	10970 ± 128	0.34	0.06	0.3 ± 7.5	1416 ± 40
$0.14 < x_F < 0.25$	0.45	0.20	5.2 ± 2.6	11509 ± 127	0.45	0.20	17.7 ± 6.2	1821 ± 44
$0.25 < x_F < 0.38$	0.53	0.31	7.6 ± 2.7	10881 ± 118	0.53	0.31	17.3 ± 5.2	2411 ± 49
$0.38 < x_F < 1.0$	0.61	0.51	6.9 ± 2.8	11033 ± 115	0.62	0.51	29.9 ± 5.6	2342 ± 51
$0.0 < p_T < 0.31$	0.21	0.17	5.3 ± 3.0	11067 ± 135	0.21	0.20	0.6 ± 6.2	1912 ± 46
$0.31 < p_T < 0.44$	0.37	0.24	−1.6 ± 3.0	9722 ± 114	0.38	0.27	18.8 ± 6.9	1656 ± 43
$0.44 < p_T < 0.61$	0.52	0.28	2.9 ± 2.7	11197 ± 116	0.52	0.31	23.7 ± 6.3	1923 ± 45
$0.61 < p_T < 1.0$	0.75	0.35	8.5 ± 2.8	10324 ± 110	0.76	0.37	22.6 ± 5.8	2058 ± 47
$1.00 < p_T < 2.5$	1.17	0.46	23.4 ± 9.0	1291 ± 44	1.17	0.47	65.8 ± 18.3	309 ± 18

The ratio S/B of the signal to the combinatorial background for each x_F and p_T range determined in accordance with Fig. 1 was used to calculate the normalization coefficient by which the histogram for the background should be multiplied when subtracting it from the data under the peak. A similar procedure was applied to Monte Carlo events, which allows us to obtain, after background subtraction, distributions over $\cos\theta_p$ for “pure” Λ hyperons both for the data and for the Monte Carlo events. The ratio of the histograms obtained in this way for the data and Monte Carlo events yields distributions over $\cos\theta_p$ for Λ hyperons adjusted for the detection and reconstruction efficiency.

The polarization of Λ hyperons is obtained by approximating the distributions over $\cos\theta_p$ in each of the ranges of x_F and p_T by the expression $dN/d\Omega = N(1 + \alpha_\Lambda P_N \cos\theta_p)$ similar to Eq. (1), where N is the normalization factor and P_N is the transverse polarization of Λ hyperons, both are fitting parameters.

The following contributions to the systematic uncertainty of the result were analyzed: (i) arbitrary choice of the approximating function and the signal range; (ii) errors in determining the efficiency of the track detectors of the setup; (iii) inaccuracy of the description of the experimental setup in the simulation; (iv) contribution from the admixture of pions and antiprotons in the kaon beam; and (v) exclusion of the distribution over $\cos\theta_p$ in the central region, $-0.25 \leq \cos\theta_p \leq 0.25$, where the background contribution is maximum, from the analysis. It was found that the contribution of the first source is dominant while other contributions can be neglected compared to it. As the upper estimate of this contribution, the polarization value without background subtraction in the region of the Λ-hyperon peak was used. The mean absolute value of the deviation of the estimated polarization P_N, in the cases with and without background subtraction is an estimate of the total systematic error ϵ_S in measuring the polarization. We obtained ϵ_S = 0.019 and 0.017 for the π^- and for K^- beams, respectively.

5. RESULTS AND DISCUSSION

Results of measuring the polarization of Λ hyperons on the π^- and K^- beams in the SPASCHARM experiment are summarized in Table 1. Average values of the Feynman variable x_F and the transverse momentum p_T, as well as the transverse polarization and the number of Λ hyperons with errors are presented. Figure 3 shows the Λ-hyperon polarization as a function of (left panel) x_F and (right panel) p_T in both reactions.

The value of P_N in the π^- beam at $p_T < 1$ GeV/c (and small x_F) is small, while it reaches (23 ± 9)% at $p_T >$ 1 GeV/c and $\sim 0.4 < x_F \lesssim 0.6$. Our experiment has provided the most accurate measurements of the polarization for the specified reaction in agreement with the results of previous experiments [21–26].

The polarization of the Λ hyperon on the K^- beam, in contrast to π^--beam data, features a significant mean positive value (18 ± 3)%. The polarization increases with x_F and p_T. In the region $p_T > 1$ GeV/c, P_N reaches (66 ± 18)%. A small (<3%) admixture of π^- mesons in the kaon beam can insignificantly increase this value. It is noteworthy that a significant number of Λ hyperons in our experiment are produced in decays of Σ^0 hyperons, the polarization of Λ

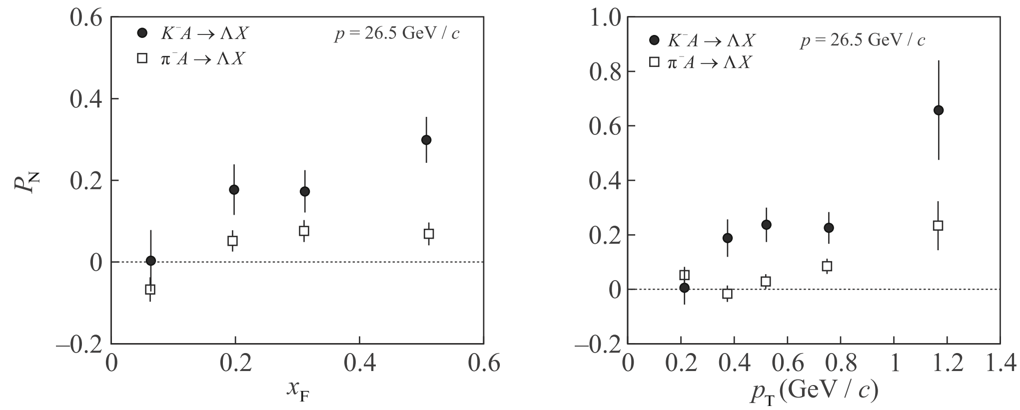

Fig. 3. Transverse polarization P_N versus the (left panel) Feynman variable x_F and (right panels) transverse momentum p_T in the $\pi^- A \to \Lambda X$ and $K^- A \to \Lambda X$ reactions obtained at 26.5 GeV/c at the SPASCHARM experimental setup at the U-70 accelerator facility (Protvino, Russia).

hyperons emerging in these decays being equal to that of Σ^0 hyperons multiplied by a factor of $-1/3$ [27]. Taking into account the polarizations of Λ and Σ^0 hyperons measured in the cited experiment on a proton beam, the contribution of these polarization can diminish the measured polarization by up to 25% compared to the polarization of "directly" produced Λ hyperons. This observation refers to almost all numerous experiments in which the polarization of Λ hyperons was measured in inclusive reactions and should be taken into account in theoretical interpretation of results.

The polarization of Λ hyperons on the K^- beam is systematically several times larger than that on the π^- beam, which may be related to the presence of the valence strange quark in the K^- meson.

The polarization of Λ on the proton beam in the $K^- p \to \Lambda X$ reaction at $x_F > 0$ is positive and increases with x_F and p_T [23, 28–33]. Our experiment has provided the only data obtained on nuclear targets. Our data also show that P_N increases with p_T and x_F. It is worth reminding that these two variables are correlated in our measurements.

The comparison of the data obtained on the π^- and K^- beams shows that the presence of a heavier valence s quarks in the initial state results in a several times larger polarization in the beam fragmentation region. It is the s quark that is the spin carrier in the Λ hyperon according to the naive quark model, while u and d quarks form a spin-singlet state. Thus, the valence s quark from a K^- meson is polarized in the process of interaction of the meson with a nucleon or nucleus with a larger probability than a sea s quark from a π^- meson.

The increase in $P_N(p_T)$ with p_T can be explained by the finer resolution of the structure of a hadron consisting of quarks, which interact via color forces according to QCD, at higher p_T values. At small p_T values, due to the uncertainty principle, an object as a whole is colorless and color forces are absent, which results in a decrease in the hyperon polarization [9, 10, 34]. The increase in $P_N(x_F)$ in the region $x_F > 0$ may be due to the increased time during which color forces act on the s quark in the model of chromomagnetic polarization of quarks [9, 10, 34].

6. CONCLUSIONS

The polarization of the Λ hyperons inclusively produced in $\pi^- A$ and $K^- A$ collisions at a momentum of 26.5 GeV/c has been measured at the U-70 accelerator facility. The polarization of Λ hyperons on the K^- beam has been measured for the first time on nuclear targets.

The π^--beam data exhibit an insignificant average ($\langle P_N \rangle = (4.1 \pm 1.4)\%$) transverse polarization of hyperons except for the region $p_T > 1$ GeV/c, where the polarization is $(23 \pm 9)\%$.

In contrast to the π^--beam data, the polarization of Λ hyperons on the K^- beam, which contains valence s quarks, has a significant average positive value ($\langle P_N \rangle = (18 \pm 3)\%$) and increases with x_F and p_T. In the region $p_T > 1$ GeV/c, P_N is as large as $(66 \pm 18)\%$.

The results obtained in the SPASCHARM experiment are the world's most accurate for such reactions. Nevertheless, in future sessions, it is of importance to increase both statistics and the accuracy of measurements, which will make it possible to determine for the first time the dependence of the polarization on the atomic number and to separately determine its dependence on p_T and x_F.

ACKNOWLEDGMENTS

We are grateful to the staff of the Accelerator Complex Department, Beam Department, Experimental Physics Department, and the Directorate of the Logunov Institute for High Energy Physics, National Research Center Kurchatov Institute for assistance and support for this work.

FUNDING

The study conducted at the Logunov Institute for High Energy Physics of the National Research Center Kurchatov Institute was supported by the Russian Science Foundation (project no. 22-12-00164). The authors from the National Research Nuclear Institute MEPhI acknowledge the support of the Ministry of Science and Higher Education of the Russian Federation (project no. FSWU-2023-0073 “New Phenomena in Particle Physics and the Early Universe”).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

OPEN ACCESS

REFERENCES

1. G. C. Mason and C. G. Wohl, Nucl. Phys. B **58**, 1 (1973).
2. G. Bunce, R. Handler, R. March, P. Martin, L. Pondrom, M. Sheaff, K. J. Heller, O. Overseth, P. Skubic, T. Devlin, B. Edelman, R. Edwards, J. Norem, L. Schachinger, and P. Yamin, Phys. Rev. Lett. **36**, 1113 (1976).
3. V. V. Abramov, Preprint IHEP 2001-13 (IHEP, Protvino, 2001); arXiv hep-ph/0111128.
4. B. Andersson, J. Phys. G **17**, 1507 (1991).
5. T. A. DeGrand and H. Miettinen, Phys. Rev. D **31**, 661 (1985).
6. D. W. Sivers, Phys. Rev. D **41**, 83 (1990).
7. J. C. Collins, Nucl. Phys. B **396**, 161 (1993).
8. M. G. Ryskin, Sov. J. Nucl. Phys. **48**, 708 (1988).
9. V. V. Abramov, Phys. At. Nucl. **72**, 1872 (2009).
10. V. V. Abramov, Phys. At. Nucl. **87**, 38 (2024).
11. W. Gerlach and O. Stern, Z. Phys. **8**, 110 (1921).
12. V. V. Abramov, I. L. Azhgirei, A. A. Borisov, et al. (SPASCHARM Collab.), Phys. Part. Nucl. **54**, 69 (2023).
13. P. A. Zyla, R. M. Barnett, J. Beringer, et al. (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).
14. V. V. Abramov, G. D. Alekseev, I. G. Alekseev, et al. (Collab. SPASCHARM), Preprint IFVE 2023-13 (Kurchat. Inst., Protvino, 2023). http://web.ihep.su/library/pubs/prep2023/ps/2023-13.pdf.
15. A. V. Ryazantsev, S. I. Bukreeva, A. N. Vasiliev, A. M. Gorin, Yu. M. Goncharenko, V. V. Moiseev, V. V. Mochalov, and P. A. Semenov, Instrum. Exp. Tech. **66**, 563 (2023).
16. A. P. Meschanin, A. N. Vasiliev, Yu. M. Goncharenko, V. A. Kormilitsyn, N. G. Minaev, V. V. Mochalov, V. L. Rykov, A. D. Ryabov, T. D. Ryabova, A. V. Ryazantsev, P. A. Semenov, S. A. Semin, and Z. G. Simonova, Phys. At. Nucl. **85** (12), 2043 (2022).
17. D. Steinschaden (for the PANDA Collab.), J. Phys.: Conf. Ser. **1085**, 042045 (2018).
18. M. Reininghaus, T. Sjöstrand, and M. Utheim, EPJ Web Conf. **283**, 05010 (2023).
19. R. Brun, GEANT—Detector Description and Simulation Tool, 1993. https://cds.cern.ch/record/1073159/files/cer-002728534.pdf.
20. J. Podolanski and R. Armenteros, Philos. Mag. **45**, 13 (1954).
21. B. Adeva, M. Aguilar, J. A. Rubio, and C. Pajareset, Z. Phys. C **26**, 389 (1984).
22. R. Sugahara, F. Ochiai, Y. Fukui, et al., Nucl. Phys. B **156**, 237 (1979).
23. F. Barreiro, O. Benary, J. E. Brau, et al., Phys. Rev. D **17**, 669 (1978).
24. P. H. Stuntebeck, N. M. Cason, J. M. Bishop, N. N. Biswas, V. P. Kenney, and W. D. Shephard, Phys. Rev. D **9**, 608 (1974).
25. S. Barlag, H. Becker, A. Bozek, et al. (ACCMOR Collab.), Phys. Lett. B **325**, 531 (1994).
26. J. Bensinger, F. Lomanno, B. D. Magnuson, et al., Phys. Rev. Lett. **50**, 313 (1983).
27. K. Heller, O. E. Overseth, G. Bunce, F. Dydak, and H. Taureg, Phys. Lett. B **68**, 480 (1977).
28. M. L. Faccini-Turluer, R. Barloutaud, C. Cochet, et al. (CERN-Sov. Collabs.), Z. Phys. C **1**, 19 (1979).
29. S. A. Gourlay, H. L. Melanson, M. A. Abolins, K. W. Edwards, W. R. Francis, H. G. Kobrak, D. P. Owen, R. A. Swanson, and P. M. Yager, Phys. Rev. Lett. **56**, 2244 (1986).

30. H. Abramowicz, R. Barloutaud, A. Borg, M. Spiro, K. Paler, T. P. Shah, S. N. Tovey, B. Chaurand, B. Drevillon, J. M. Gago, and R. A. Salmeron, Nucl. Phys. B **105**, 222 (1976).

31. H. Grassler, R. Honecker, H. Laven, L. Becker, R. Klein, W. Lohmann, H. J. Schreiber, M. F. Hodous, D. J. Kocher, D. R. O. Morrison, K.-L. Wernhard, K. W. J. Barnham, B. Pollock, D. P. Dallman, and F. Mandl, Nucl. Phys. B **136**, 386 (1978).

32. M. Baubillier, I. J. Bloodworth, G. J. Bossen, et al. (Birmingham-CERN-Glasgow-Michigan State-Paris Collab.), Nucl. Phys. B **148**, 18 (1979).

33. S. U. Chung, R. L. Eisner, S. D. Protopopescu, and R. D. Field, Phys. Rev. D **11**, 1010 (1975).

34. V. V. Abramov, A. Aleshko, V. A. Baskov, et al. (SPD Collab.), Phys. Part. Nucl. **52**, 1044 (2021).

Translated by M. Shmatikov

Publisher's Note. Pleiades Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
AI tools may have been used in the translation or editing of this article.